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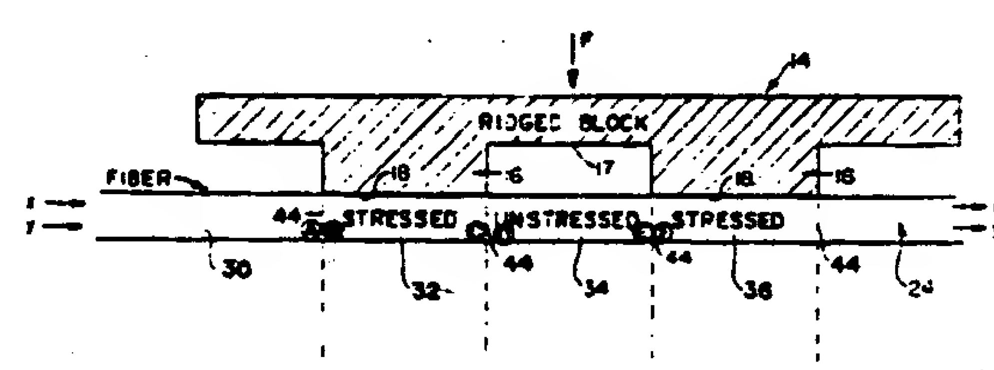
Fiber optic modal coupler.

A modal coupler, for coupling between modes of an optical ·er, such as between first and second order modes or be- ·een orthogonal polarization modes, comprises a single ntinuous strand of optical fiber (24), and a device (14) :luding a plurality of coupling surfaces (18) for applying ·ess to the optical fiber at spaced intervals along the fiber. ıe stress deforms the fiber and abruptly changes the fiber ometry at the beginning and end of each stressed region. The ange in fiber geometry causes coupling of light from the ndamental mode to the second order mode or between po- ization modes. Under certain conditions with nonbirefrin- nt fiber the coupler exhibits polarization dependence, and ıs, may be utilized as a fiber optic polarizer. In addition, ɜ device couples coherently, and may be used in interfero- ɜtric systems.



FIBER OPTIC MODAL COUPLER

Background of the Invention

The present invention relates generally to fiber optic directional couplers, and more specifically, to devices which selectively couple light energy between the propagation modes of an optical fiber. The transfer can be between fundamental and second order modes of a nonbirefringent fiber or between the polarization modes of a birefringent optical fiber.

Fiber optic directional couplers provide for the transfer of optical energy traveling in one fiber optic waveguide to another. Such couplers are useful for a variety of applications, e.g. in fiber optic sensors.

As is well known in the art, a single optical fiber may provide two or more waveguides under certain conditions. These waveguides are commonly referred to as the normal modes of a fiber, which may be conceptualized as independent optical paths through the fiber. Normal modes have unique electric field distribution patterns which remain unchanged, except for amplitude, as the light propagates through the fiber. Additionally, each normal mode will propagate through the fiber at a unique propagation velocity.

The number of modes that may be supported by a particular optical fiber is determined by the wavelength of the light propagating therethrough. The fiber has two modes of propagation, each having a different index of refraction so light propagating in one mode has a different propagation velocity than light propagating in the other mode. If the wavelength is greater than the "cutoff" wavelength, the fiber will support only a fundamental mode. If the wavelength is less than cutoff, the fiber will begin to support higher order modes. For wavelengths less than, but near, cutoff, the fiber will support only the fundamental, or first order mode, and the next, or second order mode. As the wavelength is

decreased, the fiber will support additional modes, e.g. third order, fourth order, etc.

The normal modes are orthogonal; that is, there is no coupling between the light in these modes. In addition, each of the normal modes discussed above (i.e., fundamental, second order, etc.), includes two propagation modes, called orthogonal polarization modes, which are also normal modes. These polorization modes may be defined e.g. as the linear vertical polarization mode and the linear horizontal polarization mode. The orientation of the electric field vectors of the modes defines the polarization of the light in the mode, e.g. linear vertical, or linear horizontal. A more complete discussion of these modes, and their corresponding electric field patterns, will be provided below.

Summary of the Invention

The present invention comprises an all fiber modal coupler for transferring optical power between the propagation modes of an optical fiber. The optical power is transferred from a fundamental, or first order mode, to the second order mode of a nonbirefringent optical fiber, in a controlled manner, or between the two orthogonal polarization modes of a high birefringence monomode optical fiber.

The coupler is advantageously quite simple in structure, and includes an optical fiber, having a core surrounded by a cladding, and a light sourc for introducing a lightwave into the optical fiber for propagation therethrough. The fiber has two modes of propagation, each having a different index of refraction so light propagating in one mode has a different propagation velocity than light propagating in the other mode. If a nonbirefringent fiber is used, the lightwave produced by the light source has a wavelength below the cutoff wavelength, to cause the lightwave to propagate through the fiber in both first and second order modes.

If a birefringent fiber is used, the wavelength of the lightwave produced by the light source should preferably be above the cutoff wavelength so that only the fundamental, or first order, mode propagates. The two modes are the orthogonal polarization modes of the fundamental mode.

The invention also includes a device for applying stress to the optical fiber at spaced intervals along the fiber to provide a series of stressed regions, which cause coupling of light energy between fiber modes. In the case of nonbirefringent fiber, the transfer is between the first order (i.e., fundamental) mode and the second order mode. For highly birefringent fibers the transfer is between the orthogonal polarization modes of the fundamental mode.

The stress applying device includes a support structure having a surface for supporting one side of the optical fiber, and a structure having a plurality of surfaces spaced along the optical fiber for pressing against another side of the fiber to squeeze the fiber between the support structure and the surfaces to provide a series of stressed and unstressed regions along the fiber. In the preferred embodiment, the stress applying device comprises a plate having a series of grooves cut on one face thereof to provide a series of ridges, each having a surface. These ridges are oriented perpendicular to the longitudinal axis of the fiber, and a force is applied thereto. The force is sufficient to asymmetrically deform the fiber at the stressed regions to cause a relatively abrupt change in fiber geometry at the boundary between each of the stressed regions and the adjacent unstressed regions. This abrupt change in fiber geometry causes coupling between the modes of the fiber.

In one preferred embodiment, the optical fiber is monomode birefringent fiber, and the two modes of propagation are first and second orthogonal polarization

modes. The wavelength of the source light is bel w cutoff, so that only the fundamental mode propagates. The directional coupler then preferably also includes an orientation device for holding the fiber on the fixed surface in a selectable angular orientation relative to the fixed surface, such that the axes of birefringence are at 45 degrees relative to the direction of applied pressure.

In another preferred embodiment, the two modes of propagation are first and second order modes of the fiber, and the light source introduces into the fiber a lightwave having a wave length shorter than the cutoff wave length of the fiber, so the lightwave propagates through the fiber in both of the first and second order modes.

In a preferred embodiment, the beginning of one stressed region is separated by one beat length from the beginning of the next adjacent stressed region. Further, as measured in a direction along the fiber axis, each stressed region is preferably one-half beat length, so that each of the unstressed regions will also be one-half beat length. The stressed and unstressed regions may also be odd multiples of half beat lengths. The term "beat length," as used herein, is mathematically defined as the wavelength of the lightwave propagating through the fiber divided by the difference in refractive indices of the two modes, either the first and second order modes of a nonbirefringent fiber, or the two polarization modes of a birefringent fiber. Stated another way, the beat length is the distance required for the lightwaves in different modes to separate in phase by 360°, due to the dissimilar propagation velocities of the modes.

<u>Brief Description of the Drawings</u>

These and other features of the present invention are best understo d through referenc to the drawings, in which:

Figure 1 is a schematic diagram illustrating the electric field patterns of the first and second order modes, LP_{01} and LP_{11}, respectively, of a nonbirefringent fiber;

Figure 2 is an exploded, perspective view of the modal coupler of the present invention;

Figure 3 is a cross sectional view, taken along the lines 3-3 of Figure 2, showing the shape of the ridges of a modal coupler;

Figure 4 shows a pair of ridges pressed against a highly birefringent fiber to form stressed and unstressed regions;

Figure 5 shows the effect on the axes of polarization of a birefringent fiber when stress is applied to the fiber;

Figures 6(a)-6(f) show the amount of power in the various polarization modes at various points along a periodically stressed birefringent fiber;

Figure 7 is a schematic diagram showing a pair of ridges pressed against a nonbirefringent optical fiber so as to deform the fiber and cause abrupt changes in fiber geometry at the beginning and end of each ridge;

Figures 8(a)-8(f) show the electric field distribution relative to the fiber axis at various points along a stressed nonbirefringent optical fiber;

Figure 9 is a diagram of a system using the modal coupler of the invention with a birefringent fiber;

Figure 10 is a graph of the experimentally determined modal coupling versus wavelength and of the theoretically predicted result for a highly birefringent fiber;

Figure 11 is a graph of coupled power versus wavelength, illustrating the polarization dependence and wavelength independence of the coupler used with nonbirefringent fiber, as contrasted to conventional coupled mode theory;

Figure 12 is a schematic diagram showing the circuit arrangement utilized to test the performance of the coupler of the present invention as used with nonbirefringent fiber, and to obtain the data points for the actual coupling curves shown in Figure 10;

Figure 13 is a schematic diagram of a fiber optic polarizer which utilizes the modal coupler of the present invention with nonbirefringent fiber; and

Figure 14 is a schematic diagram of a single fiber Mach-Zehnder interferometer utilizing a pair of modal couplers constructed in accordance with the present invention with nonbirefringent fiber.

Detailed Description of the Preferred Embodiment

The coupler of the present invention uses a single strand of optical fiber, which may be either nonbirefringent single mode optical fiber operated at a wavelength below cutoff such that the fiber supports both fundamental and second order guided modes, or high birefringence monomode optical fiber having two orthogonal polarization modes, preferably operated at a wavelength below cutoff so that only the fundamental mode propagates. Coherent coupling between orthogonal modes of the fiber is achieved by stressing the fiber at periodic intervals, e.g. once per beat length. The orthogonal modes provide two paths through the fiber which permit the device to be used as a two channel medium, e.g. as in in-line Mach-Zehnder interferometer, and as a two channel medium in data systems. The orthogonal modes may be either the fundamental and second order guided modes of a nonbirefringent fiber or the polarization modes of a birefringent fiber.

Before discussing the structural details and operational theory of the modal coupler of the present invention, a brief summary of mode theory will be presented, to provide background for more fully understanding the invention.

Fiber Mode Theory

When a fiber propagates light at a wavelength below cutoff, the fiber will begin to guide higher order modes. The wavelength at cutoff (λ_c) is related to the fiber geometry, and may be calculated utilizing the following equation:

$$\lambda_c < \frac{2\pi r \; n_c^2 - n_{cl}^2}{2.405} \qquad (1)$$

where r is the core radius, n_c is the refractive index of the core, and n_{cl} is the refractive index of the cladding.

Those skilled in the art will recognize that the fundamental mode, second order mode, etc. each comprise plural electric field patterns, each of which represents a mode. For example, the fundamental mode includes two polarization modes. To avoid confusion, the fundamental mode will be referred to henceforth as the fundamental set of modes and the second order mode will be referred to as the second order set of modes.

The lowest order, or fundamental, set of modes which is guided is the LP_{01} mode set. If the indices of the core and cladding are approximately equal, then it can be shown that the LP_{11} mode set is the next mode set (i.e. the second order mode set), which is guided beyond the fundamental mode set LP_{01}. These mode sets are defined and described in detail in an article by D. Gloge, entitled "Weakly Guiding Fibers", Applied Optics, 10, 2252 (1971).

Figure 1 shows the field patterns of the two modes in the fundamental LP_{01} set of modes and the four modes in the second order LP_{11} set of modes. The arrows indicate the direction of the electric field vectors at a particular instant in time.

For the LP_{01} set of fundamental modes, the electric field vector is either vertical, representing vertically polarized light or horizontal, representing horizontally polarized light. However, for the LP_{11} set of second order modes, the vertical polarization and the horizontal polarization each have two electric field patterns. Further, each of the second order mode set field patterns comprises two lobes. In one of these field patterns, the electric field vectors of the lobes are perpendicular to the zero electric field line (ZFL), while in the other electric field pattern, the electric field vectors f the lobes are parallel to the zero electric field lin (ZFL). The zero electric field line is simply a line between the two lobes in each of the second order mode patterns which represents zero electric field amplitude. Similarly, the horizontally polarized second order modes have electric field vectors oriented either parallel to the ZFL or perpendicular to the ZFL, as shown in Figure 1.

Each of the six electric field patterns in Figure 1, namely, the two LP_{01} patterns and the four LP_{11} patterns, are orthogonal to each other. Thus, the six patterns or modes may be viewed as independent optical paths through the fiber, which ordinarily do not couple with each other.

If the indices of the core and the cladding are approximately equal, the two LP_{01} modes will travel through the fiber at approximately the same propagation velocity, and the four second order LP_{11} modes will travel through the fiber at approximately the same propagation velocity. However, the propagation velocity for the fundamental LP_{01} set of modes will be slower than the propagation velocity for the second order LP_{11} set of modes. Thus, light traveling in the two set of modes LP_{01}, LP_{11}, will move in and out of phase with each other as the light propagates through the fiber. The rate at

which the modes LP_{01}, LP_{11} move in and out of phase depends on the difference in the effective refractive indices between the two sets of modes LP_{01} and LP_{11}.

The birefringence of a fiber is the difference in the effective refractive indices of the two polarization modes, and is designated Δn. If the source light is at a wavelength above cutoff, only the two polarization modes within the LP_{01} set of modes will propagate through the fiber. Although there is very little difference between the propagation velocities of these two polarization modes for nonbirefringent fiber, the difference in the refractive indices for the two polorization modes, and thus, the difference in propagation velocities between the two modes, increases as the birefringence of the fiber increases. Because light propagating in birefringent fiber travels at different velocities in different polarization modes, the relative phase between light in one polarization mode and light in the other polarization mode will shift continuously, thereby causing the light in the two polarization modes to move in and out of phase with each other as the light propagates through the fiber.

A single high birefringence monomode optical fiber is capable of maintaining the polarization of light traveling therein for long distances, so that there is ordinarily no appreciable coupling of light from one mode to the other. These polarization modes are generally referred to as the X and Y polarization modes. The total birefringence of the fiber may generally be assumed to be independent of wave length.

Beat Length

The beat length of a fiber is the distance it takes two signals of the same frequency traveling in different propagation modes of the fiber at different velocities to shift 360° in relative phase so they are again in phase. Mathematically, the beat length is expressed as:

$$L = \frac{\lambda}{\Delta n} \qquad (2)$$

where λ is optical wave length in a vacuum and Δn is the difference in the effective indices of two propagation modes of the fiber. If birefringent fiber is used in the coupler of the present invention, Δn is equal to the difference in the effective refractive indices between the two polarization modes (X,Y) of the LP_{01} set of modes. If nonbirefringent fiber is used in the present invention, Δn is equal to the difference in effective refractive indices between the first order set of modes (LP_{01}) and the second order set of modes (LP_{11}).

Coherent power transfer between the two sets of modes, LP_{01} and LP_{11} sets in nonbirefringent fiber, or the X and Y polarization modes in birefringent fiber, can be achieved by producing periodic coupling between the modes that matches the beat length of the modes. Such coupling can be implemented by periodically deforming the fiber with the device shown in Figure 2.

Structural Features of the Coupler

Figure 2 shows the coupler of the present invention in perspective view. A polished, flat surface 10 is machined on a metal or plastic block 11. The surface 10 should be smooth and flat to within a few microns. An optical fiber is disposed between the surface 10 and the undersurface of a second block 14, which has a multiple ridge region 12, machined thereon. The ridge region 12 provides a series of ridge-shaped coupling elements, which, when pressed against the fiber so as to squeeze the fiber between the blocks 11, 14, stress the fiber at periodic intervals to cause light to be coupled between the modes.

Referring briefly to Figure 3, there is shown a cross section of the ridged region 12 in which a plurality of ridges 16 are formed. The ridges 16 are formed by machining the block 14 to provide spaced parallel notches

or grooves 17, such that there is formed a plurality of polished ridge surfaces 18, each having a width, W, and providing a separation, S, between the edges of adjacent ridges. In the embodiment shown, the width, W, and separation, S, are each one-half beat length of the fiber for light at the particular frequency which is utilized. In theory, the width W of each ridge 16 can be any odd multiple of one-half beat length, and the separation S between adjacent ridges can be any odd multiple of one-half beat length.

The cross section of the notches 17 in the preferred embodiment is rectangular, since that is the easiest shape to machine. However, this shape is not critical; any shape that yields a flat surface 18 on the ridges 16 will be satisfactory, provided the height, H, of the notch 17 is sufficient to maintain stress when the material of the ridge 16 is deformed by application of force to the fiber. In a preferred embodiment, the block 14 is made of a hard plastic, such as Deltrin™. This plastic deforms more readily than glass, and thus avoids damage to the fiber when stressing the fiber. For complete power transfer, it is important that the ridges apply stress to the fiber so as to provide alternate regions of deformation and no deformation in the fiber. The overall length of the device is not critical; however, in the embodiment shown, the length is on the order of two to three inches. Further, it has been found that when nonbirefringent folder is used, a force of about 3 kg applied to the block 14 is required to achieve maximum coupling, regardless of the number of ridges 16.

Returning to Figure 2, the block 14 has a plurality of holes 20 spaced in a pattern to receive a set of pins 22 projecting from the flat surface 10 in a matching pattern. The block 14 may be slid toward and away from the flat surface 10 along the pins 22. The pins 22 are so aligned and the ridges 16 are oriented such that the edges

of the ridges 16 are transverse to the longitudinal axis of a fiber 24, which is held on the flat surface 10 by a pair of fiber holding plates 26. Thus, the edges of the ridges 16, illustrated by the reference numeral 27 in Figure 3, are transverse to the longitudinal axis of the fiber 24. The pins 22 also serve to prevent rocking of the block 14 to prevent uneven pressure from being applied to the fiber 24.

If desired, the ends of the pins 22 may be threaded for receiving respective nuts (not shown), and respective coil springs (not shown) may be placed between the nuts and the upper block 14 in order to control the pressure exerted by the top plate 14 on the fiber 24.

The holding plates 26 are disk-shaped with a V-shaped cutout therein for receiving the fiber, and are mounted in respective circular apertures of respective end plates 28, which are mounted at the ends of the block 11 so that they are perpendicular to the flat surface 10. However, any other suitable method of holding the fiber may be used alternatively.

Determining the Fiber Beat Length

To properly size and space the ridges 16, the beat length of the fiber 24 must be known. For birefringent monomode fiber, the beat length may be directly observed, as is known in the art. However, the beat length of nonbirefringent fiber cannot be directly observed, and a more elaborate procedure is necessary. A method of determining the beat length of a nonbirefringent fiber will now be described.

A particular nonbirefringent fiber used as the fiber 24 in testing was a single length of Corning single mode fiber, having an outer diameter of approximately 125 μ, a cutoff wavelength of approximately 650 nm, a mean index for the core and the cladding of 1.458, a step index profile with a core index f 1.4593, a cladding index of 1.4567, and a core radius of 2.9 μ. Vertically polarized

light was input to the fiber by offsetting the input beam relative to the central axis of the fiber such that approximately equal amounts of the vertically polarized fundamental LP_{01} mode and the vertical-normal LP_{11} mode (See Figure 1) were launched. A continuous wave dye laser was used so that the input wavelength could be varied.

The fiber output was displayed on a screen and the interference pattern between the two guide modes was observed. As the input wavelength was scanned from 570 nm to 610 nm the output pattern fluctuated periodically (i.e. repeated itself) 40 times. Those skilled in the art will understand that, from this data, the difference between the refractive indices of the two sets of modes (i.e. the first and second order sets of modes) may be calculated using the simplified Eigen value equations for a cylindrical step index fiber, as discussed in Chapter 8 of Light Transmission Optics, Dietrich Marcuse, 2nd edition, Van Nostrand Reinhold Co., 1982 (See especially Section 8.6).

For the above-described fiber, a value for the refractive index difference Δn was calculated to be 0.001342, yielding a beat length, calculated in accordance with equation (2), above, of 0.447 mm for a wavelength of 600 nm.

For testing with this nonbirefringent fiber, the preferred embodiment of the coupler of the invention was constructed as a thirty ridge structure with 0.203 mm wide gaps between ridges 16, and 0.229 mm wide ridges, yielding a ridge periodicity of .432 mm. The gaps and ridges were not equal in length due to fabrication limitations. The wavelength required for a beat length of 0.432 mm (equal to the ridge periodicity) was calculated to be 608 nm.

Theory of Operation for Birefringent Fiber

As shown in Figure 4, application of a vertical force, F, to the plate 14 presses the ridges 16 against the fiber 24, and thus, causes the portions of the fiber 24 beneath

the ridges 16 to be stressed. The ridges cause abrupt changes in fiber geometry at the beginnings and ends of the stressed regions. For purposes of explanation, these abrupt changes in fiber geometry may be viewed as boundaries 44.

It is important to the operation of the device that abrupt changes in the orientation of the polarization mode axes be caused so that such changes in orientation occur over a very short boundary region. In the embodiment shown, these boundaries 44 in Figure 4 are formed by the edges of the coupling surfaces 18 of the relief areas 16, and thus, are periodically spaced at one-half the beat length. In other embodiments, the boundaries 44 could be spaced at odd multiples of one-half the beat length.

At each boundary 44 light is coupled between the modes of the fiber 24. For a birefringent fiber 24, the inventors found that the orthogonal axes of polarization X and Y (which correspond to the polarization modes X and Y) abruptly shift at each boundary 44 through an angle θ to orthogonal axes of polarization X' and Y', as shown in Figure 5. This abrupt shift was quite unexpected, since it was believed that stress applied by the surfaces 18 would deform the fiber 24 so as to perturb the axes of polarization over a longer region than the width W of the surface 18 applying the stress. This would tend to cause a gradual shift in the orientation of the axes of polarization over a relatively long boundary region rather than an abrupt shift at the edges of the surfaces 18 of the ridges 16. Such a gradual rotation of the axes of polarization over a relatively long distance would not cause a significant power transfer, i.e., coupling between the polarization modes, because the resultant polarization vector would merely follow the gradual shift in the axes of polarization, and substantially maintain its position relative thereto.

Modal Coupling in a Birefringent Fiber

Figures 6(a)-6(f) show how the abrupt boundaries 44 in the fiber 24 cause power transfer in a birefringent fiber. The electric field vector for the X-polarization mode (which corresponds to the X axis of polarization in a birefringent fiber) is labeled X in the unstressed regions 30, 34, and X' in the stressed regions 32, 36. Similarly, the electric field vector for Y-polarization mode (which corresponds to the Y-axis of polarization) is labeled Y in the unstressed regions 30, 34, and Y' in the stressed regions 32, 36. It will be understood that the X and X' vectors [Figs. 6(a)-6(f)], correspond to the X and X' axes (Figure 5) of polarization, respectively, and the Y and Y' vectors [Figs. 6(a)-6(f)] correspond to the Y and Y' axes (Figure 5) of polarization, respectively.

In Figure 6(a) the input light is represented by the vector 48 as entering the fiber 24 with all power in the X polarization mode. This polarization is maintained as the light propagates in the unstressed region 30 up to the first boundary 44 at the beginning of the first stressed region 32, at the location A in Figure 4.

Figure 6(b) shows the power components after the light has propagated just beyond the first boundary 44 into the stressed region 32 and is at the location B in Figure 4. At that first boundary 44, the axes of polarization X and Y abruptly shift through an angle θ (Figure 5) to a new orientation X' and Y', as discussed above in reference to Figure 5. These new polarization mode axes X' and Y' represent the orientations of the electric field vectors for the electromagnetic light waves traveling in these polarization modes. As in the X and Y orientation case, the light in the X' mode travels at a different velocity than the light in the Y' mode, since that is fundamental to the concept of birefringence. The overall polarization of the light then is the resultant vector based upon the components of power in the X' and Y' or X and Y axes.

It will be noted that in the stressed region 32, there first appears at the location B (Figure 4) a component of power in the Y' polarization mode, whereas at the location A, before the first boundary 44, there was no power in the Y mode. The reason for this stems from Maxwell's equations, which are well known mathematical relationships that explain the behavior of electromagnetic fields at boundaries. A fundamental principle is that, at an abrupt boundary through which an electromagnetic field passes, the orientation and magnitude of the electric field vector, relative to a fixed observer, must be the sam on either side of the boundary. In this case, the resultant polarization, i.e., the orientation of the electric field vector at the location A (Figure 4) is as shown by the vector 48 in Figure 6(a). To the right of the first boundary 44, at the location B, the polarization axes X' and Y' are shifted so that to maintain the resultant polarization for the vector 48, there must be a small Y' component because X' is shifted from its orientation in the X mode. Thus some power is transferred from the X mode into the Y' mode at the first boundary 44.

As the two X' and Y' components travel through the stressed region 32 from the location B to the location C, they shift in relative phase by 180 degrees, because the stressed region is one-half a beat length long. The relative phase of the X' and Y' components at the location C, to the left of the second boundary 44, is as shown in Figure 6(c). The 180 degree phase shift is modeled by reversing the direction of the Y' component. The same result would be obtained if the 180° phase shift was modeled by reversing the direction of the X or X' vector and leaving the Y or Y' vector unchanged. As a consequence of this 180° phase shift, the resultant polarization vector 50 is shifted from the orientation of the vector 48.

At the second boundary 44, the orientation of the polarization axes X' and Y' abruptly shifts back to the original orientation X and Y by virtue of the removal of stress. As the light travels across the second boundary 44, the polarization represented by the vector 50 must be preserved. The situation at the location D, to the right of the second boundary 44, at the beginning of the unstressed region 34, is as shown in Figure 6(d). However, because the shifting of the axes of polarization cause a concomitant shift in the direction of the component vectors representing power in the X and Y modes, the magnitude of the X and Y components must change to preserve the angle and magnitude of the overall electric field vector 50. By comparing Figures 6(a) and 6(d), it will be noted that through the regions 32, 34 a substantial increase has occurred in the magnitude of the Y component of power.

Figure 6(e) represents the power components at the location E (Figure 4), just to the left of the third boundary 44 ending the unstressed region 34. The unstressed region 34 is also one-half beat length long and thus there will be another 180° phase shift between the X and Y components as they travel through the region 34. This phase shift is again modeled by reversing the direction of the Y component at the boundary 44, as shown in Figure 6(e). By extension of the above discussion, it is apparent that the polarization axes will shift abruptly again at the boundary 44, from the X and Y orientation, back to the X' and Y' orientation (Figure 5). This causes more power to be shifted into the Y' polarization mode, and it can be seen from Figure 6(f) depicting the situation at the location F, just right of the boundary 44, that to preserve the magnitude and angle of the resultant electric field vect r 52 across the boundary 44, the magnitude of the Y' component in Figure 6(f) must

increase because of the shift in the angles of the X and Y axes to X' and Y'.

The modal coupler for birefringent fiber can be characterized mathematically. As discussed above, for highly birefringent fiber, light propagating down one of the axes typically will not couple appreciably to the other axis. It has been demonstrated that an additional birefringence can be induced by applying pressure to the fiber. This additional birefringence is given by

$$\Delta n_p = \frac{an^3Cf}{2d} \quad (3)$$

where a is a constant equal to 1.58 for round fiber, n is the mean refractive index of the fiber, C is a piezo-optical coefficient, f is the force per unit length applied to the fiber and d is the fiber cladding diameter. In calculations, the values $n = 1.46$, $C = 5 \times 10^{-12}$ (MKS), and $d = 65\ \mu m$ were used.

For small forces, the additional birefringence can be treated as a perturbation to the fiber's normal birefringence. For the purpose of analysis it is assumed that the force is applied at 45° to the fiber axes of birefringence. Applying the force at an angle of 45° to the axes of birefringence causes the maximum shift in the orientation of the birefringence axes per unit force. However, the angle is not critical and deviations from 45° can be adjusted for by increasing the applied force. The first order result of the perturbation of birefringence is rotation of the fiber's original axes of birefringence through a small angle. This small shift in birefringence does not significantly change the magnitude of the total fiber birefringence, Δn. The angle θ is given by

$$\theta \sim \sin(\theta) = \left[\frac{\Delta n_p^2}{2(\Delta n_p^2 + \Delta n^2 + \sqrt{2}\Delta n \Delta n_p)}\right]^{1/2} \qquad (4)$$

The total birefringence, Δn, is assumed to be constant with wavelength; it can be measured by directly observing the beat length $L = \lambda/(\Delta n)$ of the fiber at a known vacuum wavelength, λ. The fiber used in the preferred embodiment had a measured $\Delta n = 7.4 \times 10^{-4}$.

Light originally polarized along the X axis will decompose into components polarized along the axes X' and Y' when entering a squeezed region. The relative phase of the light in the two polarizations will change by π radians in half a beat length. If at this distance the force on the fiber is removed, the light will decompose back into components along the original axes with an amount $\cos^2(2\theta)$ in the X polarization and $\sin^2(2\theta)$ in the Y polarization. After traveling another L/2 distance the proper phase relationship in the two axes will be established such that a second stressed region will cause further power transfer. For a single L/2 length stressed region and L/2 unstressed region, a Jones matrix, T, can be written to describe the amplitude polarization transformation of this structure

$$T = \begin{bmatrix} -\cos 2\theta & \sin 2\theta \\ -\sin 2\theta & -\cos 2\theta \end{bmatrix} \qquad (5)$$

Repeating such a structure N times yields a total polarization transformation matrix

$$T^N = \begin{bmatrix} (-1)^N \cos 2N\theta & (-1)^{N+1} \sin 2N\theta \\ (-1)^N \sin 2N\theta & (-1)^N \cos 2N\theta \end{bmatrix} \qquad (6)$$

Therefore, complete coupling from one polarization to the other can be achieved by applying a force, F, to the N ridges such that $2N\theta = \pi/2$. For large N (>5) this optimal force is given by

$$F \sim \frac{L\sqrt{2}\,\Delta n d\pi}{4an^3C} \qquad (7)$$

For example, if N = 10 and L = 32 mils, using the numbers given above, a force of 177 grams would be needed for complete coupling.

The ridges of the coupler of the present invention must be designed for a particular wavelength, because the beat length of the light in the fiber is not constant as a function of wavelength. When the device is used at a different wavelength, the phase shift, $\Delta\Phi$, over a ridge length changes from π radians to $\pi + 2\delta$ radians. Consequently, complete power transfer can no longer take place. Assuming proper force applied by each ridge so that $2N\theta = \pi/2$, the transfer matrix over a single ridge and gap period becomes

$$T = \begin{bmatrix} \sin^2\theta - \cos^2\theta e^{i2\delta} & \sin\theta\cos\theta\,[1+e^{i2\delta}] \\ -\sin\theta\cos\theta\,[1+e^{-i2\delta}] & \sin^2\theta - \cos^2\theta e^{-i2\delta} \end{bmatrix} \qquad (8)$$

If the light is originally launched in only one polarization, after N ridges the power coupled into the second polarization is given by $|\kappa|^2$, where

$$\kappa = -\sin\theta\cos\theta\,[1+e^{-i2\delta}]\,\left[\frac{\sin(N\cos^{-1}b)}{\sqrt{1-b^2}}\right] \qquad (9)$$

where: $b = \sin^2\theta - \cos^2\theta\cos 2\delta$.

The off diagonal elements of the transfer matrix represent the amount of amplitude coupling which will occur between polarization modes. This amplitude coupling, κ, is the value of each of the two off-diagonal matrix elements of T^N.

Theory of Operation for Nonbirefringent Fiber

Referring to Figure 7, a modal coupler incorporating a nonbirefringent fiber 24 is shown. A force F is applied to the upper block 14, which causes the coupling surfaces 18 of the ridges 16 to press against the fiber 24 and asymmetrically deform the fiber. The ridges 16 cause abrupt changes in fiber geometry at the beginning and end of each stressed region 32, 36, thus creating boundaries 44 between the stressed and unstressed regions.

For the nonbirefringent fiber 24, the center line or longitudinal axis 46 of the fiber is abruptly shifted at each boundary 44 in the direction of the applied force. Such abrupt shifting of the fiber axis 46 causes light to be coupled from the fundamental LP_{01} set of modes to the second order LP_{11} set of modes at each of the boundaries 44. The particular second order mode to which the light is coupled depends upon the direction of force relative to the polarization of the applied light. For example, if the input light in the fundamental is vertically polarized, such light will uniquely couple to the vertical-perpendicular second order mode, and not to the vertical parallel second order mode, the horizontal-normal second order mode, or the horizontal parallel second order mode (see Figure 1). Assuming now that the force is still vertical, but the input light is horizontally polarized in the fundamental mode, such light will couple uniquely to the horizontal parallel second order mode and not to any of the other second order modes.

Modal Coupling in a Nonbirefringent Fiber

To more fully illustrate the manner in which light is coupled to the second order set of modes at each of the

boundaries 44 in a nonbirefringent fiber 24, the electric field distribution of a lightwave will be traced as it propagates through the fiber 24, from the left side to the right side, as viewed in Figure 7. It will be assumed that the lightwave is vertically polarized and launched in the fundamental mode.

As shown in Figure 8(a), just before the lightwave arrives at the first boundary 44, e.g. when it is at the location A in Figure 7, the electric field distribution, illustrated by the curve labeled 53, will be symmetric about the fiber axis or center line 46, and well confined to the fiber core.

As the lightwave crosses the first boundary 44, to the location B in Figure 7, the electric field distribution shown by the curve 53 will appear the same, relative to a fixed observer, since the electric field is continuous across the boundary 44, in accordance with Maxwell's equations. However, the fiber axis 46 is now shifted due to the deformation of the fiber 24 caused by the ridges 16, so that the curve 53 is no longer symmetrical about the axis 46, as shown in Figure 8(b). The curve 53, shown in dotted lines in Figure 8(b), thus decomposes back into two normal modes, namely a fundamental mode, illustrated by the curve 54, and a small second order mode, illustrated by the curve 56. In other words, the nonsymmetric curve 53 is the sum of the first and second order normal mode curves 54, 56, respectively. Thus, at the first boundary 44, the decomposition of the curve 53 causes a small amount of fundamental mode light to be transferred to the second order mode.

Since the ridge 16 is one-half beat length long, as the light propagates from location B to location C in Figure 7, the light in the second order mode will undergo a phase shift of 180° relative t the light in the first order or fundamental mode. Acc rdingly, at the point C in Figure 7, the electric field distributions shown by the

curves 54 and 56 will be the same, except that they are 180° out of phase, as illustrated in Figure 8(c). When the lightwave crosses the second boundary 44, and arrives at the point D in Figure 7, the axis 46 of the fiber shifts back to an unstressed, undeformed condition, and the modes 54, 56 are again nonsymmetrical with regard to the axis 46. Consequently, the light in the fundamental mode 54 again decomposes into a fundamental mode 58 of lesser amplitude than the mode 54, and a second order mode which is in phase with the second order mode 56, thereby yielding a resultant second order mode 60, as shown in Figure 8(d), which has an increased amplitude relative to the mode curve 56. It will be recognized that the 180° phase change between the modes during propagation from point B to point C advantageously causes the light coupled from the fundamental to the second order mode to add to that previously coupled, such that the second order mode coupling is cumulative, rather than destructive.

As the light propagates from point D to point E, the first and second order modes undergo another 180° phase change, such that when the light reaches point E in Figure 7, the electric field distribution is as shown in Figure 8(e). At the third boundary 44, the fiber axis 46 again shifts, and the same process repeats, so as to cause light from the fundamental mode to be coupled to the second order mode, as illustrated by the curves 62, 64 in Figure 8(f). Thus, it may be seen from the foregoing that the abrupt boundaries 44 provide coupling locations at which a fraction of energy from the fundamental mode is coupled to the second order mode.

Performance of the Modal Coupler

From the above discussion, it is seen that each boundary 44 at an odd multiple of one-half beat length along the fiber 24 causes a certain amount of power to be coupled from one mode to the other. The power coupled at the boundaries 44 is additive, so that total amount of

coupled power from one end of the fiber 24 to the other is cumulative. If the boundaries were other than at exact odd multiples of one-half beat length, the cumulative coupled power might still be non zero, but each boundary at other than an odd multiple might cause power to be coupled into the other mode which has a component which is out of phase with the power already coupled into the other mode. This out of phase coupled power would cancel some of the power already coupled. Whether the net coupled power was non zero would depend upon the exact locations of the boundaries and how much force was applied in each stressed region. In general, however, errors of e.g. on the order of 5-10% in the location of the boundaries may be tolerated without having a substantial adverse effect on the operation of the invention.

The preferred embodiment of the modal coupler of the invention was tested using both birefringent and nonbirefringent fiber. In the device depicted in Figure 2, the fiber jacket was removed from the fiber 24 to expose the fiber directly to the ridges. This may not be necessary in all cases.

Testing With Birefringent Fiber

Figure 9 shows a system using the coupler described above in reference to Figures 1-6, for coupling between polarization modes of a birefringent fiber, labeled with the reference numeral 64. A frequency tunable dye laser 66 was used to generate the source light. This light, polarized by a standard polarizer 68, is launched into a length of elliptical core birefringent fiber 24 by a lens 70 which focuses the polarized light onto the core of the fiber. The polarizer 68 is aligned to pass light into only one of the two orthogonal polarization modes of the fiber 24. The light propagates into the fiber 24, through the polarization coupler 64, and has some or all of its power coupled into the other, orthogonal, polarization mode, upon exiting the fiber 24 at the fiber segment 74.

A lens 72 collimates light emerging from the output fiber segment 74 and causes a beam 75 thus formed to fall on a beam splitter 76. The beam splitter 76 causes part of the beam 75 to be directed to a standard photo-detector 78 and the remaining part of the beam 75 is passed through a polarizer 80. The polarizer 80 only passes light of the same polarization relative to the polarization established by the polarizer 68. The light passed through the polarizer 80 is impressed upon a standard photo-detector 82. The outputs of the detectors 82 and 78 are input, by lines 86, 88, respectively, to a standard ratiometer which indicates the relative power in the orthogonal polarization compared to the total output power.

With the polarizer 80 at the output, an extinction ratio between the fiber polarizations of between 19 and 32 dB was measured. The extinction ratio is the logarithm to the base 10 of the ratio of the optical power in the vertical polarization mode to the optical power in the horizontal polarization mode. An extinction ratio of at least 19 dB was achieved regardless of wavelength when the wavelength was changed. It is believed that this limit is set by scattering loss in the fiber (>150 dB/km), because some of the scattered light remains guided. At certain wavelengths, the ratio improved up to 32 dB, probably due to destructive interference of the scattered light. When the ridged block 14 was placed on the fiber and pressure was applied, a coupling ratio greater than 32 dB was achieved, typically with a force of about 220 grams. The coupling ratio is the logarithm to the base 10 of the ratio between the optical power not coupled to the orthogonal polarization mode and the power that is coupled into the orthogonal mode. This ratio was observed with 10 ridges at 633 nm and with 30 and 60 ridges at about 608 nm light wavelength.

The dependence of coupling on wavelength was investigated experimentally using a dye laser tunable

between 569 nm and 614 nm. The device used was a 60 ridge coupler whose center wavelength was at 609 nm, to which uniform optical pressure was applied. The experimental setup was the same as shown in Figure 9. The light left in the original polarization, i.e., not coupled, is the detected signal. The ratiometer 84 was used to compensate for laser power fluctuations as the wavelength was changed. The results are plotted in Figure 10, which shows experimental results as dots, and the theoretically predicted results, based upon the abrupt shift in birefringence model assumed for the system, as a solid line. The good agreement between the two curves supports the conclusion that the changes in birefringence at the boundaries of the stressed regions are indeed abrupt. A full width at half maximum which is theoretically equal to approximately λ/N, was observed to be 9 nm. However, the side lobes were higher than predicted due to uneven pressure of the ridges on the fiber. This unequal pressure was probably caused by variations in the fiber diameter and ridge height on the order of angstroms, and can be dealt with by constructing individually weighted ridges. The width of the central peak indicates the potential of this polarization coupler for use as a multiplexer or notch filter.

Testing With Nonbirefringent Fiber

When using nonbirefringent fiber, test results show that the coupler of the present invention exhibits surprising anomalous behavior when compared to conventional coupled mode theory. For example, conventional coupled mode theory predicts that the coupler should be wavelength dependent. However, the test results show that the coupling is substantially independent of the wavelength of the light over a broad range.

From the analysis above in relation to coupling between modes in nonbirefringent fiber, one would expect the performance of the coupler to be dramatically reduced

when the spacing between the beginning of one ridge and the beginning of the next ridge 16 is not one beat length (or an integer multiple thereof). Calculations show that, in theory, the performance of the coupler of the present invention used with nonbirefringent fiber should generally follow the curve 90 of Figure 11. For the preferred embodiment, maximum coupling was expected to occur at a wavelength of 608 nm, which yields a beat length equal to the ridge periodicity of 0.432 mm. At wavelengths above or below 608 nm, the curve 90 predicts that the coupling should rapidly decrease.

The performance of the thirty ridge coupler of the preferred embodiment was tested with nonbirefringent fiber utilizing the circuit arrangement shown in Figure 12. A frequency tunable dye laser 92 was used to produce the source light. This source light was impressed upon a beam splitter where approximately one-half of the light was directed to a detector 94, while the other one-half was impressed upon a lens 96, which focused the light for introduction into a nonbirefringent optical fiber 98. The dye laser 92 was operated in a wavelength range below cutoff such that only the first and second order modes were launched in the fiber 98.

The fiber 98 was wrapped around a 1.3 centimeter diameter post at the input end to provide a mode stripper 100 for stripping out any second order modes that were launched. This type of mode stripper is well known in the art, and is discussed in an article by Y. Katsuyama, entitled "Single Mode Propagation in a Two Mode Region of Optical Fiber by Using Mode Filter", Electronics Letters, 15, 442 (1979). An all fiber polarization controller 102 was formed in the fiber 98 after the mode stripper 100. A polarization controller of this type is disclosed in U.S. Patent No. 4,389,090, issued June 21, 1983. The purpose of the polarization controller 102 was to vary the polarization of the guided input light such that it is

e.g. linear vertical. The fiber 98 then passed through a ridge structure such as that described in reference to Figures 2 and 3 to form the thirty ridge modal coupler 104 of the preferred embodiment. The fiber was then wrapped around another post to form a second mode stripper 106, identical to the first mode stripper 100. At the output end of the fiber, the output light is directed against a collimating lens 108, which impresses the output light upon a detector 110. The two detectors 94, 110 are then connected by lines 112, 114, respectively, to a ratiometer 116. This ratiometer 116 displays, as an output, the ratio of the output light intensity, as measured by the detector 110, to the input light intensity, as measured by the detector 94.

In operation, the light input at the input end of the fiber 98 is first stripped of second order modes by the mode stripper 100, so that when the light enters the polarization controller, only the fundamental mode is present. The polarization controller is then used to adjust the polarization of the input light so that it is e.g. vertically linearly polarized upon entering the modal coupler 104. The coupler 104 is operated by applying a force to the upper ridged plate, as discussed above, to cause coupling of light from the fundamental mode to the second order mode. After leaving the coupler 104 the light is stripped of second order modes by the mode stripper 106, and any residual light in the fundamental mode is impressed upon the detector 110 through the lens 108.

For testing, the wavelength of the input light was varied from 570 nm to 612 nm to determine the sensitivity of the coupler 104 to variations in wavelength. As expected, maximum coupling occurred at a wavelength of 608 nm. Measurements indicated that the coupling of the vertically polarized fundamental mode to the second order mode (i.e. the vertical-perpendicular second order mode)

was quite good, and that less than -40 dB of residual power was left in the fundamental mode at the output end of the fiber 98, which corresponds to 99.99% of the power being coupled from the fundamental to the second order mode. Insertion loss was measured by removing the output mode stripper 106 and measuring the total power in the fiber while the coupler was operating. By comparing this value to the power in the fiber when the coupler was not operating, a loss of 9% was measured.

When the wavelength of the source light was varied from 608 nm, however, the coupler 104 exhibited unexpected behavior. Specifically, the coupling of the vertically polarized light remained at a high level throughout the wavelength range from 570 to 612 nm, as illustrated by the curve 118 in Figure 11, and thus, the coupling did not follow the theoretical curve 90. The triangles on the curve 118 indicate actual data points.

The tests described above in reference to Figure 11 were repeated, this time for linearly horizontally polarized input light. As indicated by the curve 120 of Figure 11, coupling of the horizontal polarization was relatively constant over the wavelength range, and peaked at 608 nm. Dots on the curve 120 represent actual data points. Thus, the coupling curves 118, 120 for vertically and horizontally polarized light, respectively, were both broad and did not follow the predicted coupled mode theory curve 90. It is significant, however, that the curve 120 for horizontally polarized light exhibits further anomalous behavior in that the amount of coupling is much less than for vertically polarized light, being on the order of only 4 dB. For both the curves 118 and 120, a vertical force was applied to the coupler 104 to cause coupling from the fundamental to the higher order modes.

Thus, the coupler of the present invention exhibits anomalous behavior when used with nonbirefringent fiber, when compared to conventional coupled mode theory, in that

(1) the coupling is relatively constant for different wavelengths, and (2) such coupling is polarization dependent. Interestingly, the polarization dependence of the coupler also appears to be related to the number of ridges 16 (Figure 3). For example, when a ten ridge device is used, the discrepancy between the coupling of the two polarizations diminishes, and both polarizations couple on the order of 99% of their power into the second order mode. For an eighty ridge device, neither polarization couples better than 20% of its power. The reasons for this surprising behavior of the coupler are not fully understood. It is theorized that the coupler does not follow conventional mode theory for two reasons: (1) because the LP_{11} modes only approximate the true normal modes of the fiber, and (2) because the normally nonbirefringent fiber becomes birefringent when squeezed by the ridges 16 (Figure 3).

Use of the Coupler as a Fiber Polarizer

The above-described polarization dependence of the coupler when used with nonbirefringent fiber may advantageously be used to provide an in-line all fiber bidirectional polarizer. As shown in Figure 13, such a polarizer may comprise a single continuous strand of fiber 122 having end portions 124, 126. Mode strippers 128, 130 are located at the end portions 124, 126, respectively, and a modal coupler 132, such as the thirty ridge coupler of the preferred embodiment, is interposed between the mode strippers 128, 130. Preferably, the number of ridges 16 on the modal coupler 132 is selected to maximize coupling in one polarization, (e.g. the vertical polarization) and minimize coupling of the orthogonal polarization (e.g. the horizontal polarization). As discussed previously in reference to Figures 11 and 12, using the thirty ridge device, 40 dB coupling of the vertically polarized fundamental mode t the higher order mode was achieved, while only 4 db of the horizontally

polarized fundamental mode was coupled to the higher order mode. Consequently, such a modal coupler yields a 36 dB extinction ratio between the vertical and horizontal polarizations in the fundamental modes. In operation, light is input to one end portion of the fiber 122, e.g. the end portion 124. Second order modes are stripped by the mode stripper 128 so that only the fundamental mode enters the modal coupler 132. It will be assumed that vertical polarizations are well coupled, while horizontal polarizations are poorly coupled. Thus, if the light input to the coupler 132 is vertically polarized, substantially all of it will be coupled to the second order mode, and such light will be stripped by the mode stripper 130 so that the amount of light reaching the output fiber portion 126 is virtually zero. On the other hand, if the polarization of the input light entering the coupler 132 is horizontal, only a fraction of the light will be coupled to the second order mode and stripped by the mode stripper 130. Thus, much of the light will remain in the fundamental mode and propagate to the output end portion 126 of the fiber 122. Thus, input light which is horizontally polarized is passed by the coupler and mode stripper, while vertically polarized light is effectively blocked with nonbirefringent fiber. As indicated above, with a thirty ridge device, a 36 db extinction ratio between the vertical and horizontal polarizations in the fundamental modes may be expected, yielding an all-fiber polarizer with performance comparable to that of thin polarizing films.

<u>Use of the Coupler as a Mach-Zehnder Interferometer</u>

As shown in Figure 14, a Mach-Zehnder interferometer may be constructed by mounting two modal couplers 140, 142 in spaced relationship along a single continuous strand of nonbirefringent optical fiber 144. Source light is produced by a laser 146, which is optically coupled to introduce light into the input end of the fiber 144. The

source light from the laser 146 is first passed through a mode stripper 148, formed on the fiber 144, to remove second order modes. The light is then passed through a polarization controller 150, which is used to adjust the polarization of the light to, e.g., linear-vertical. The guided source lightwave then enters the first coupler 140, which is set to approximately 50/50 coupling, such that half of the power is coupled to the second order mode.

After propagating a distance through the fiber 144, the light then enters the second coupler 142. The light exiting the second coupler 142 passes through a mode stripper 152, formed on the fiber 144, to strip second order modes. The light then exits the fiber 144 and is impressed upon a detector 154, which outputs an electrical signal on a line 156.

In the embodiment shown, the length of fiber between the modal couplers 140, 142 and the wavelength of the source light are selected such that, at the input end of the second coupler 142, there is zero phase difference between the light in the first order and second order modes. It will be recognized that if the phase difference between the modes is zero upon entering the coupler 142, the coupling to the second order mode will be at a maximum, while if the first and second order modes are 180° out of phase, the coupling by the coupler 142 will be at a minimum. Accordingly, with zero phase difference at the input end of the coupler 142, maximum coupling to the second order mode will occur. The second order mode is then stripped by the mode stripper 152, and the signal at the detector, i.e. the residual fundamental mode power, will be at a minimum. The amount of coupling of the coupler 142 may be varied until a minimum in the residual fundamental power is observed. The coupling is then fixed at this value and the portion of fiber between the couplers 140, 142 is exposed e.g. to an environmental quantity to be measured, such as temperature.

Exposure to temperature will change the length of the fiber between the couplers 140, 142, and thus, cause the light in the first and second order modes to move out of phase upon entering the coupler 142. This will cause the coupling to the second order mode to decrease, and thus, the residual power in the fundamental mode, as measured by the detector, will increase. The output signal on the line 156 from the detector 154, therefore, provides a direct indication of the magnitude of the sensed environmental quantity. In one experiment, a dynamic range of the power in the fundamental mode of 30 dB was measured as the fiber was thermally expanded. This demonstrates that the device couples coherently and can be used in interferometric systems.

Use of the Coupler as an Amplitude Modulator

The modal coupler described with reference to Figure 2-4 above and configured in the system shown in Figure 9 can be used with highly birefringent fiber as an amplitude modulator. By varying the force F in Figure 4 in accordance with a modulating signal, a varying amount of power can be coupled from the X polarization mode to the Y polarization mode, with the amount of coupling proportional to the magnitude of the force F. That is, if any conventional transducer 158 (Figure 9) is driven e.g. sinusoidally to vary the force F applied to the ridged block 14 of the polarization coupler 64, the optical power in the Y polarization mode of the fiber 24 will be directly proportional to the magnitude of the force F, where the input power is launched initially all in the polarization mode X. From Equation (3) it is seen that the additional birefringence induced by the stress is directly proportional to the force applied per unit of length. When the force varies, the angle through which the axes of the polarization modes shift changes per Equation (4). This changes the amount f power shifted between the polarization modes by changing the amount of

power decomposing onto each of the new axes at each boundary as will be apparent from inspection of Figures 6(a) - 6(f).

Conclusion

Thus, the modal coupler of the present invention has a variety of uses, e.g. as a single fiber polarizer, a single fiber Mach-Zehnder interferometer, or an amplitude modulator. Additionally, the coupler may be used in a two channel data system. These uses are exemplary only, and other uses will be apparent to those skilled in the art.

Although the invention has been described in terms of the preferred embodiment, many variations will be apparent to those skilled in the art. All such variations using the same principle are intended to be included within the appended claims.

CLAIMS

1. A directional coupler characterized by:

an optical fiber (24) having two modes of propagation, each of said modes of propagation having a different effective index of refraction, so that light propagating in one of said modes has a different propagation velocity than light propagating in the other of said modes;

a light source (66) for introducing a lightwave into said optical fiber (24);

a support structure (10), having a surface for supporting one side of said optical fiber (24); and

a structure (14) having a plurality of surfaces (18) spaced along said optical fiber, for pressing against another side of said fiber, such that said fiber (24) is squeezed between said surfaces (18) and said support structure (10) to provide a series of alternating stressed and unstressed regions (32, 34, 36) along said optical fiber.

2. The directional coupler defined in Claim 1 wherein each of said surfaces (18) has abrupt edges to provide abrupt changes in the geometry of said fiber at the beginning and end of each stressed region (32, 36).

3. The directional coupler defined in either of Claims 1 or 2, wherein the width (W) of each surface (18) in the direction of the fiber axis is approximately equal to an odd multiple of one half the fiber beat length and the spacing (S) between adjacent surfaces (18) in the direction of the fiber axis is approximately equal to an odd multiple of one half the fiber beat length.

4. The directional coupler defined in any of Claims 1 through 3, wherein (i) said lightwave has a wavelength selected to cause only the fundamental (LP_{01}) set of modes to propagate in said fiber, (ii) said optical fiber (24) is a monomode, birefringent fiber, and (iii) said two

modes of propagation are the two orthogonal polarization modes of the fundamental LP_{01} set of modes.

5. The directional coupler defined in Claim 4, further characterized by an orientation device (26, 28) for holding said fiber (24) on said support structure (10) so that the axes of birefringence of said fiber are in a selected angular orientation relative to said surface of said support structure.

6. The directional coupler defined in Claim 5, wherein said orientation device is characterized by fiber holding plates (26) rotatable relative to said support structure (10) to rotate said fiber about its longitudinal axis.

7. The directional coupler defined in any of Claims 1 through 3, wherein:

said fiber is substantially nonbirefringent;

said modes of propagation are the fundamental (LP_{01}) set of modes and the second order (LP_{11}) set of modes of said fiber (24); and

said lightwave has a wavelength shorter than the cutoff wavelength of said fiber so that said lightwave propagates through said fiber only in the fundamental (LP_{01}) set of modes and the second order (LP_{11}) set of modes.

8. The directional coupler defined in any of Claims 1 through 7, wherein said surfaces (18) are on a ridged block (14), and said support structure comprises a flat plate (10).

9. The directional coupler defined in Claim 8, wherein the coupler is further characterized by a plurality of pins (22) projecting from said support structure (10), and a plurality of holes (20) in said ridged block (14), wherein said holes (20) and said pins (22) are c rrespondingly arranged so each of said pins is aligned with and fits into one of said holes, so said

ridged block (14) can be slid toward and away from said flat plate (10) on said pins.

10. The coupler defined in any of Claims 1 through 9, further characterized by a modulating driver (158) for oscillating said surfaces (18) relative to said support structure (10) in accordance with a modulating signal to vary the stress applied to said fiber (24) in said stressed regions (32, 36).

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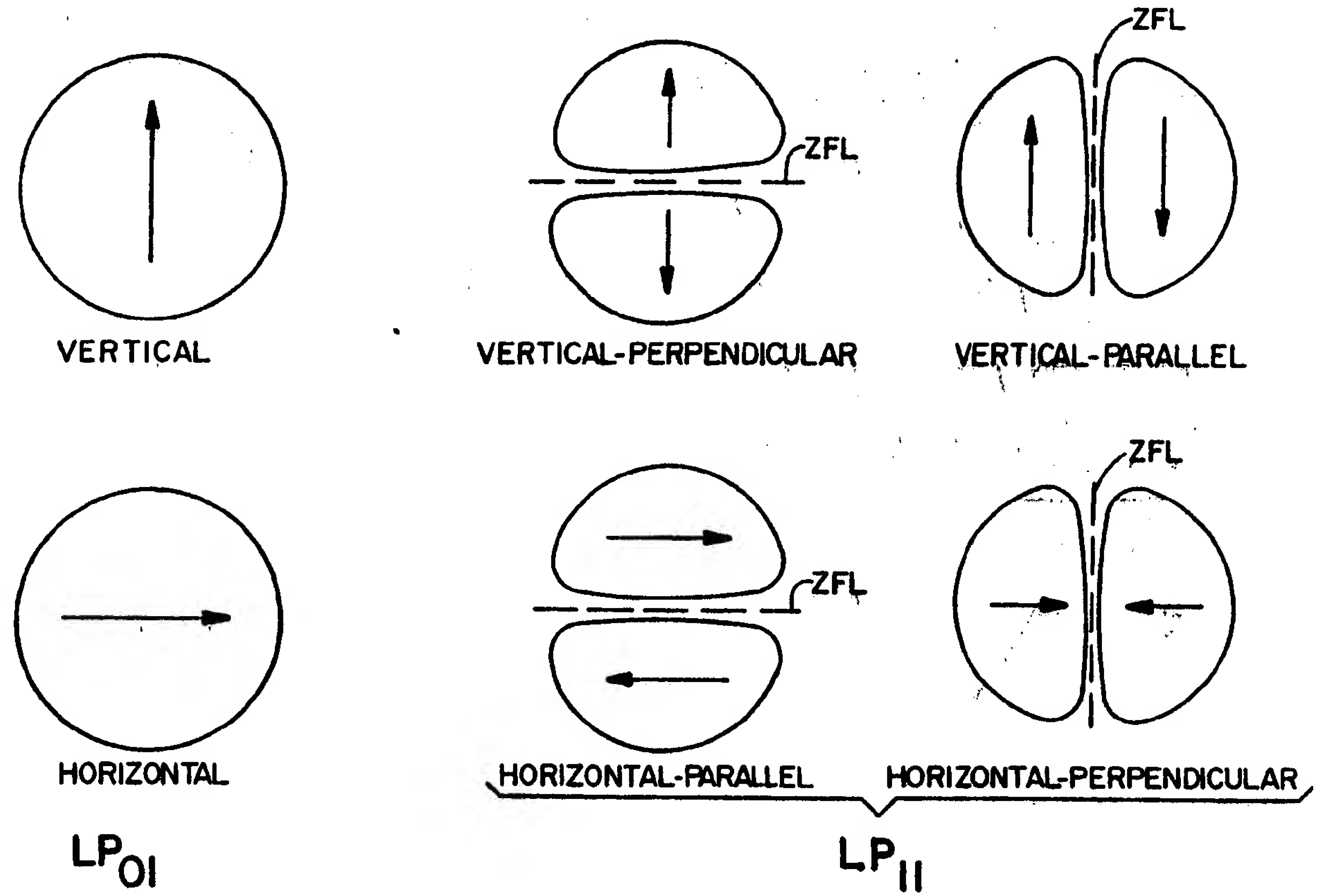
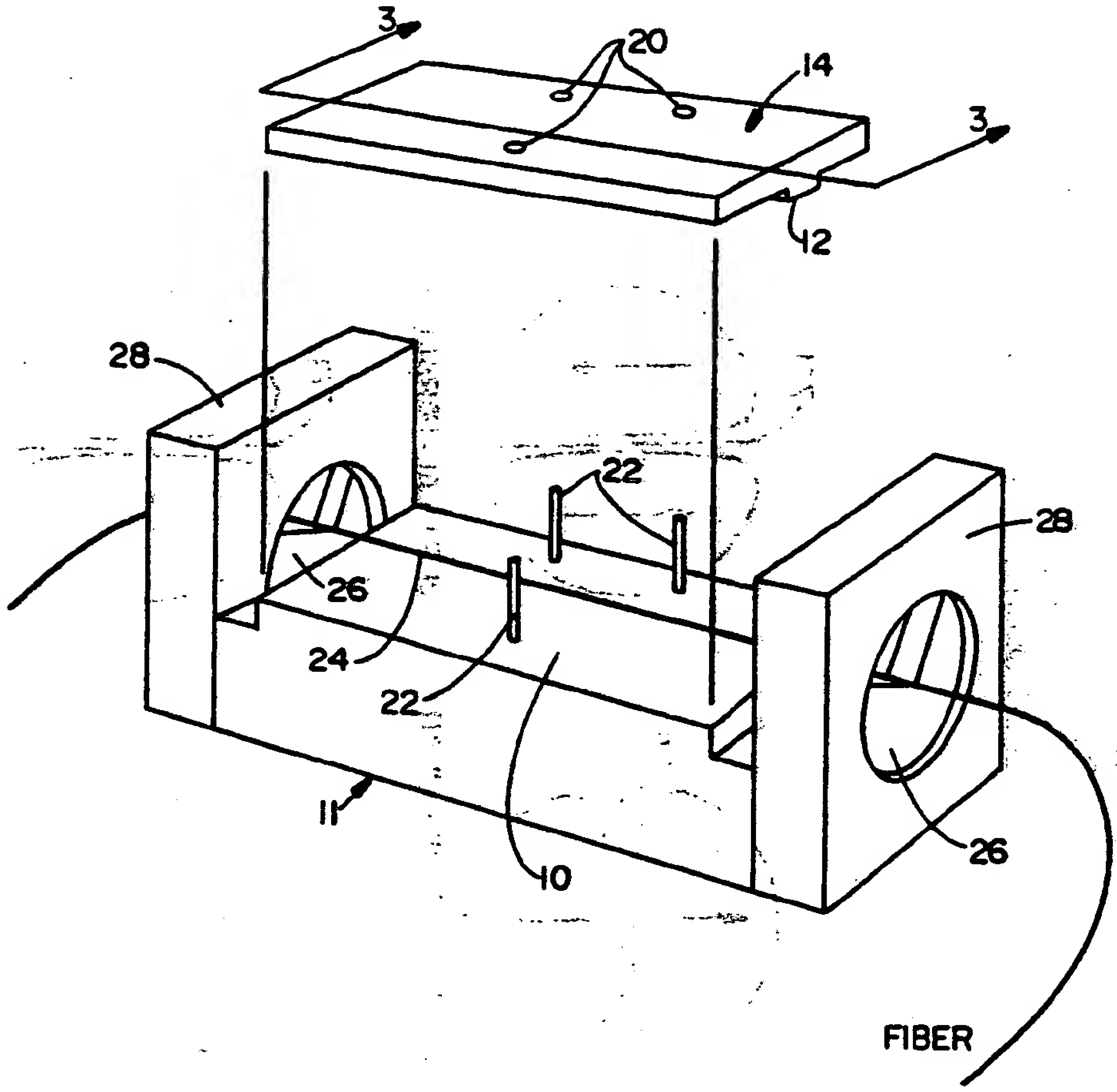


ZFL
ZFL
ZFL
ZFL
VERTICAL
VERTICAL-PERPENDICULAR
VERTICAL-PARALLEL
HORIZONTAL
HORIZONTAL-PARALLEL
HORIZONTAL-PERPENDICULAR
LP_{01}
LP_{11}

FIG. 1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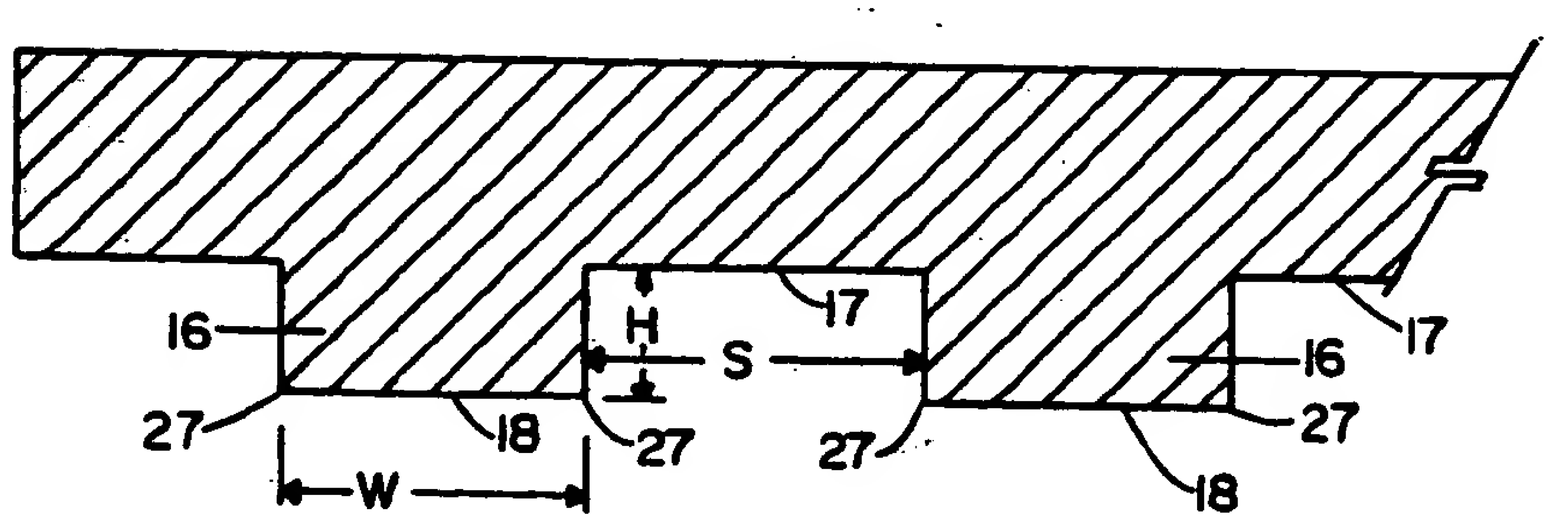
FIBER

FIG. 2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W
18

FIG. 3

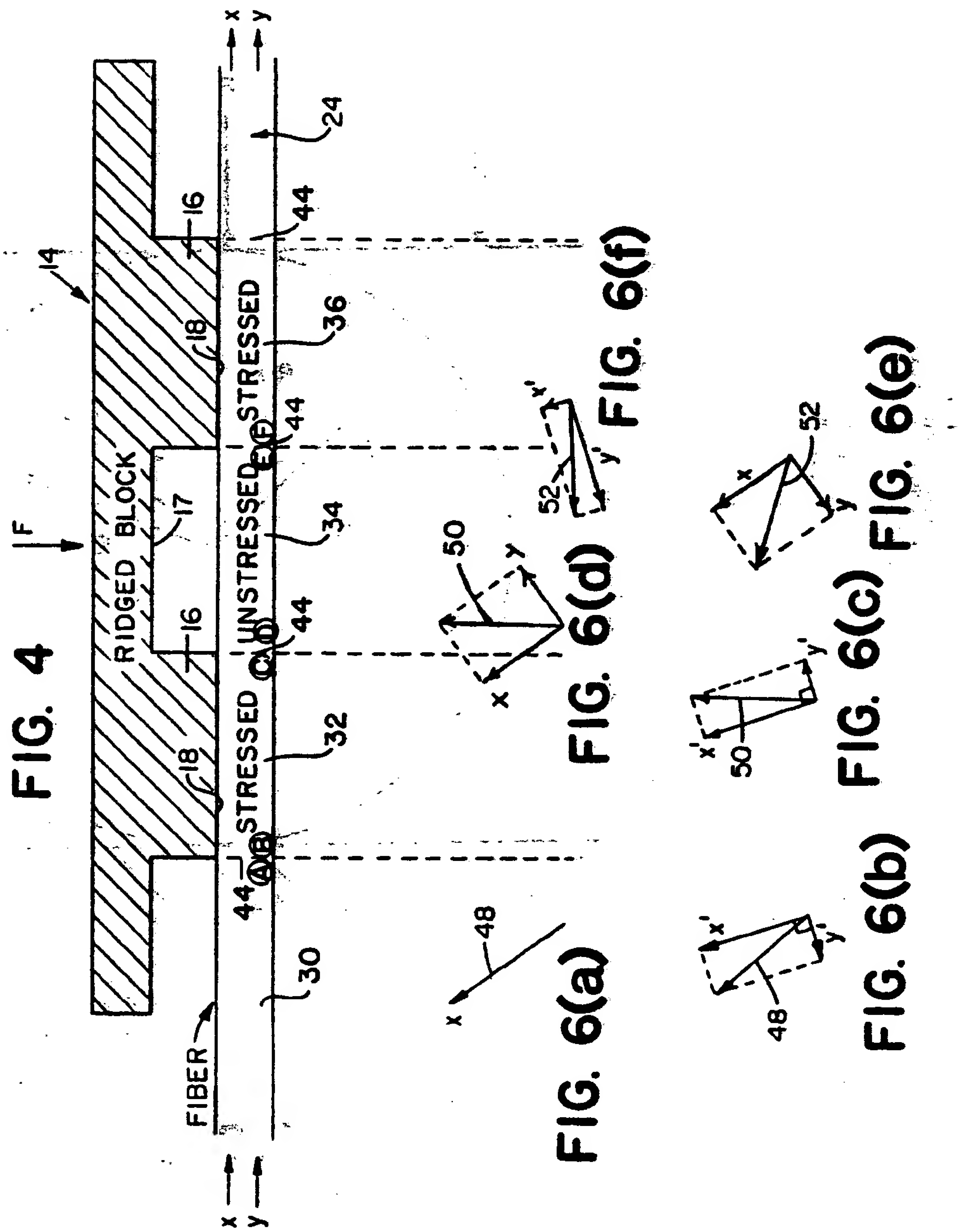


FIG. 4

FIG. 6(a)

FIG. 6(b)

FIG. 6(c)

FIG. 6(d)

FIG. 6(e)

FIG. 6(f)

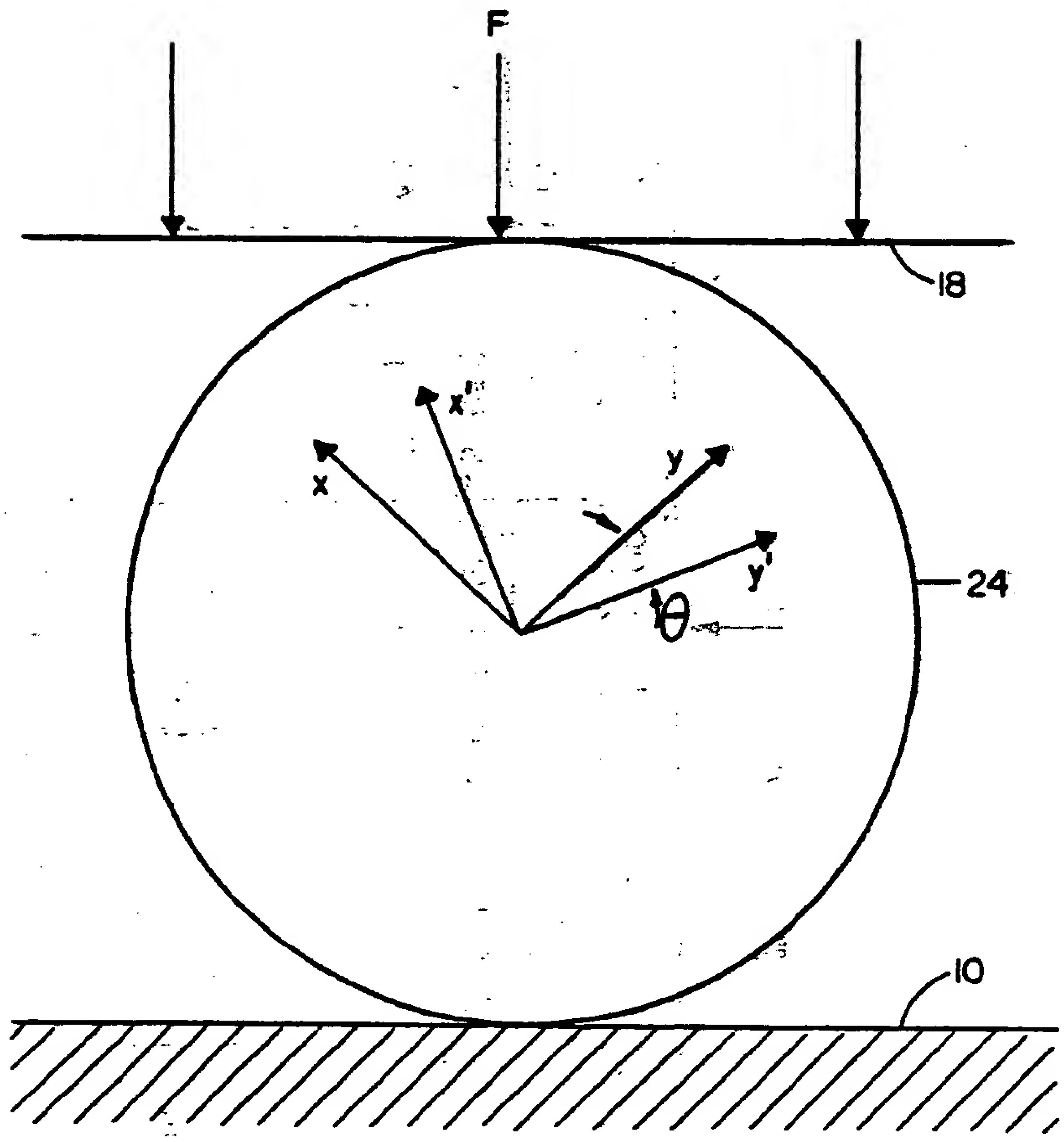
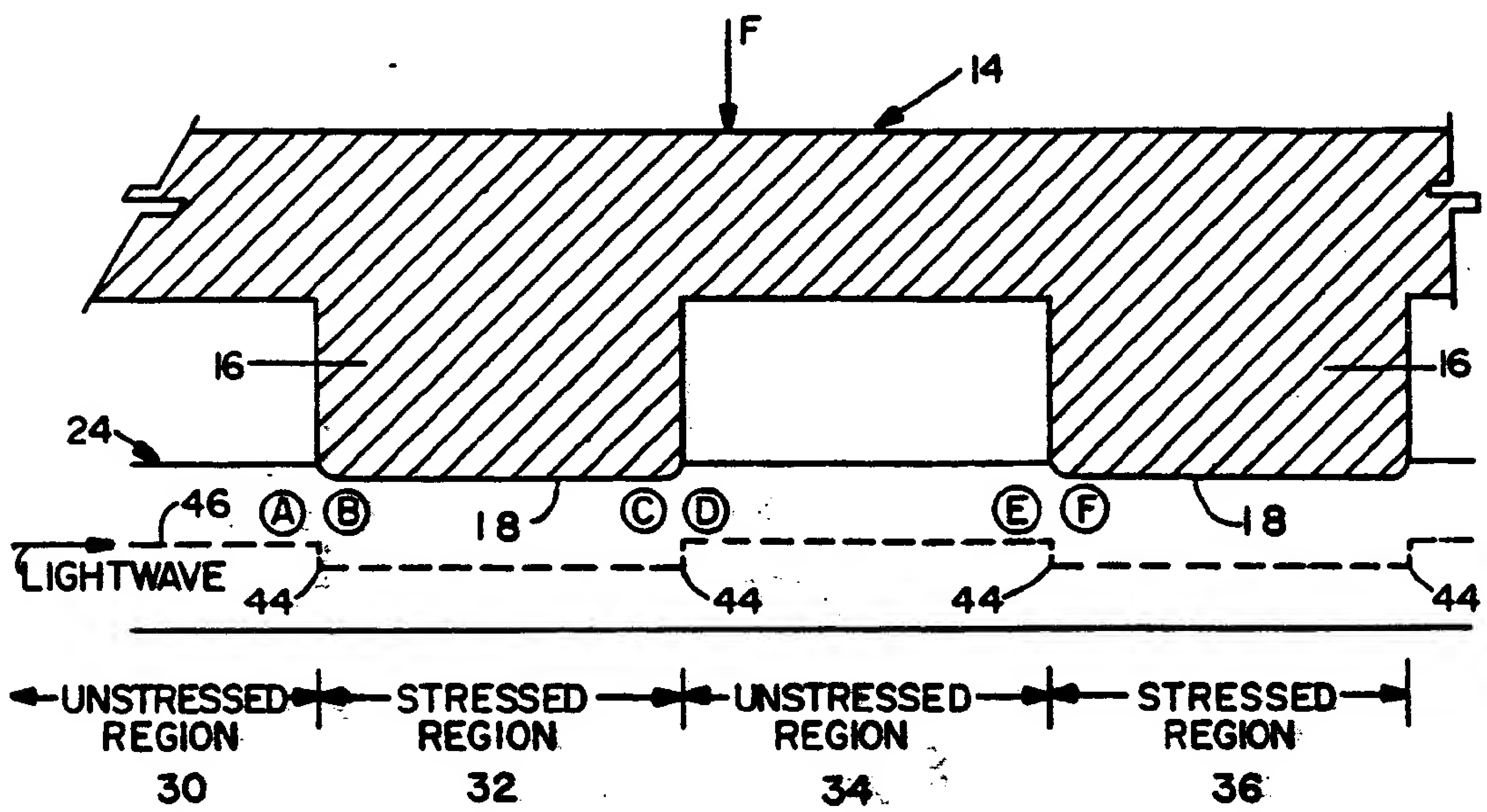


FIG. 5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24
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A B
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C D
E F
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LIGHTWAVE
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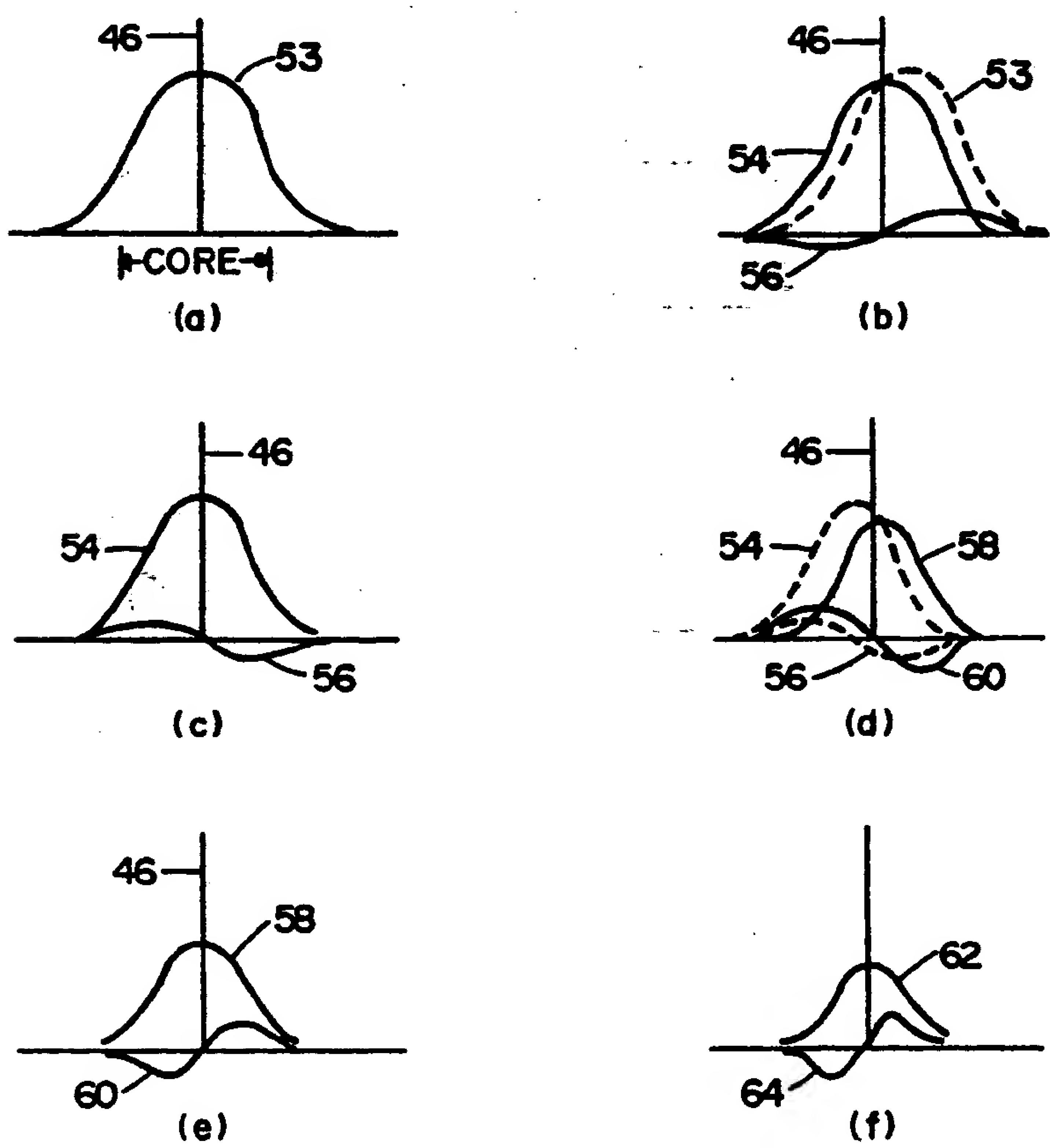
STRESSED REGION 32
UNSTRESSED REGION 34
STRESSED REGION 36

FIG. 7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CORE
(a)
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(b)
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(c)
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56
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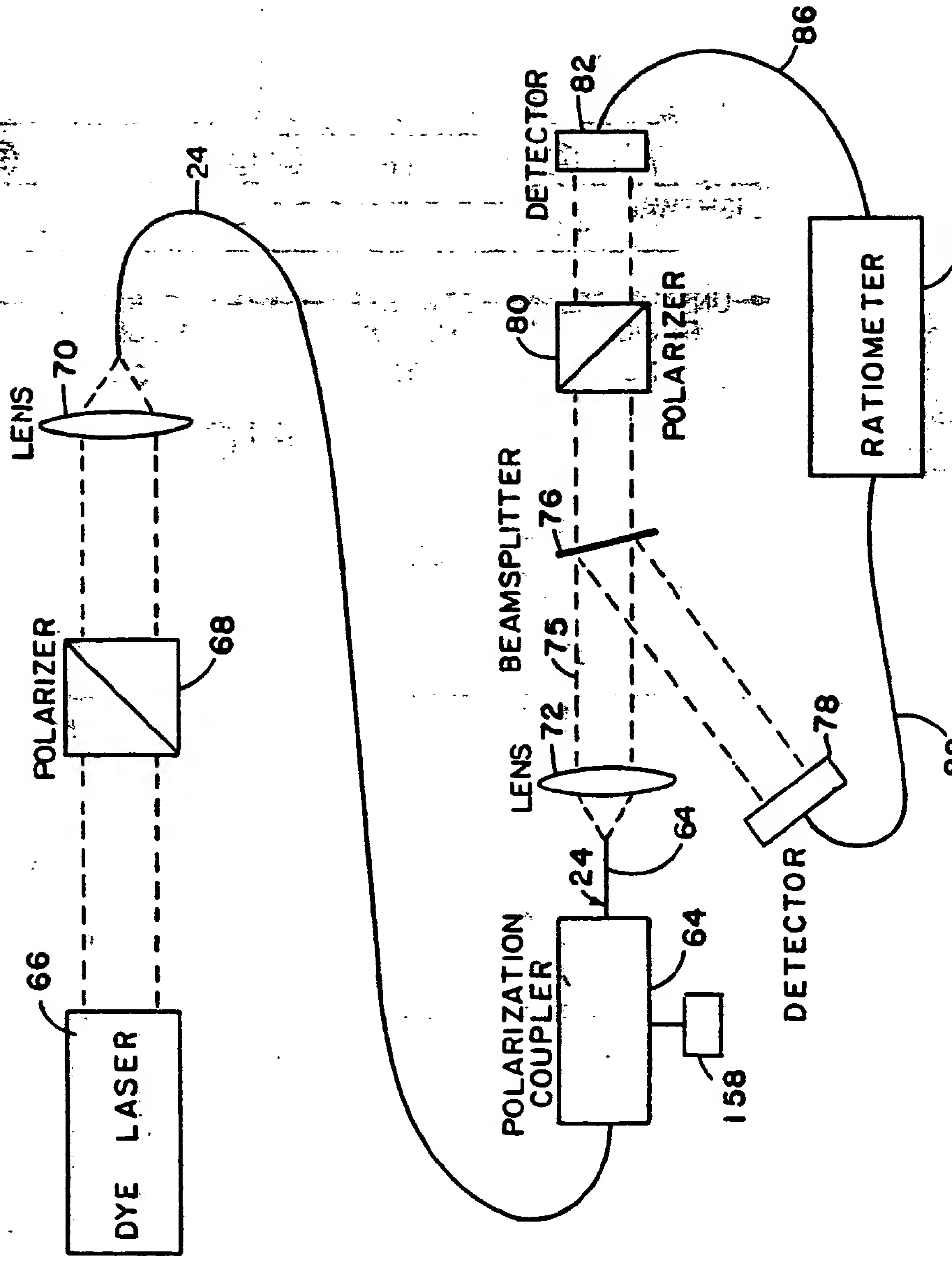
(d)
46
58
60
(e)
62
64
(f)

FIG. 8



DYE LASER
66
POLARIZER
68
LENS
70
24
POLARIZATION COUPLER
64
158
24
64
LENS
72
75
BEAMSPLITTER
76
DETECTOR
78
POLARIZER
80
DETECTOR
82
86
RATIOMETER
84
88

FIG. 9

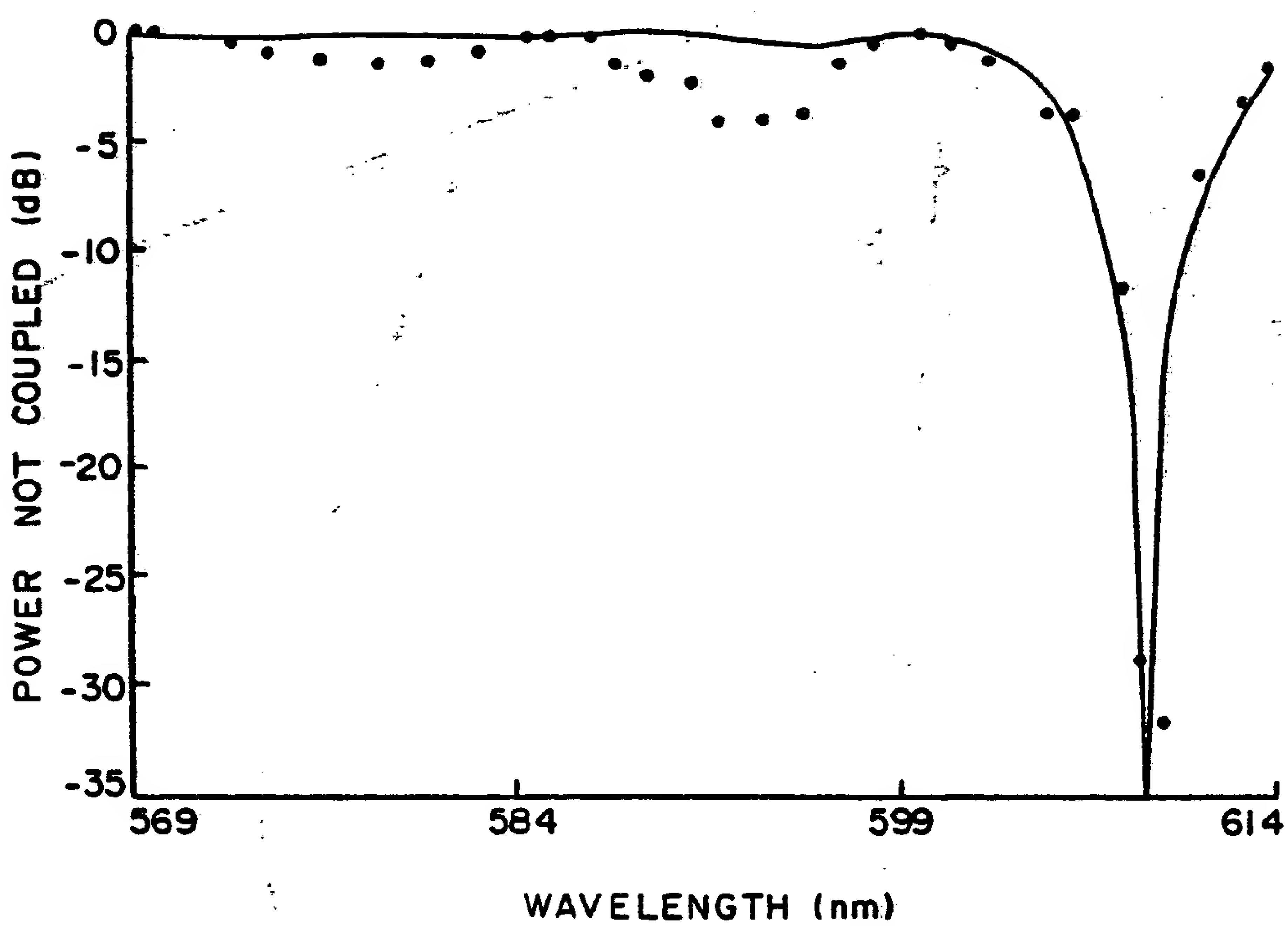

POWER NOT COUPLED (dB)
0
-5
-10
-15
-20
-25
-30
-35
569
584
599
614
WAVELENGTH (nm)

FIG. 10

0143583

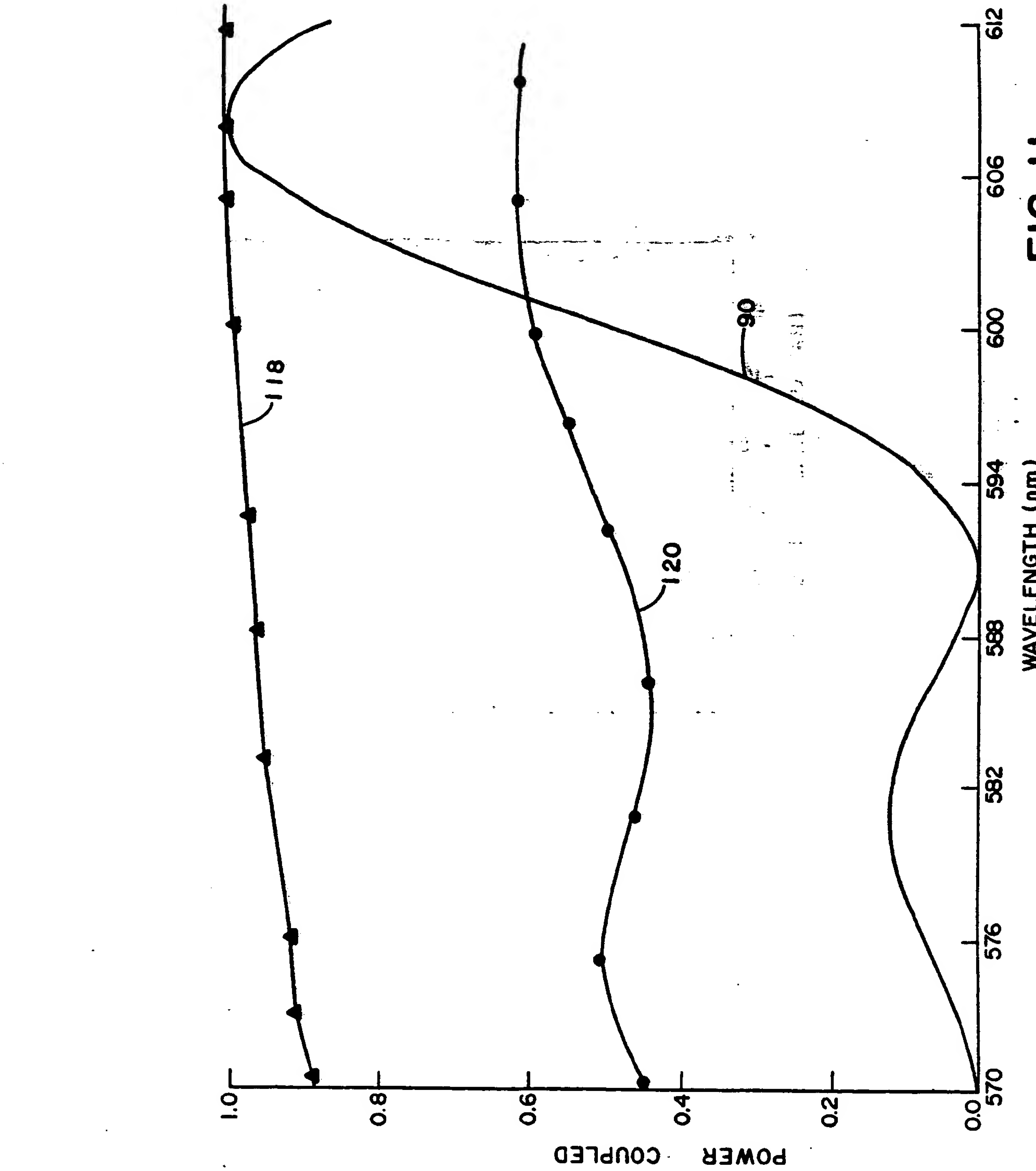


FIG. 11

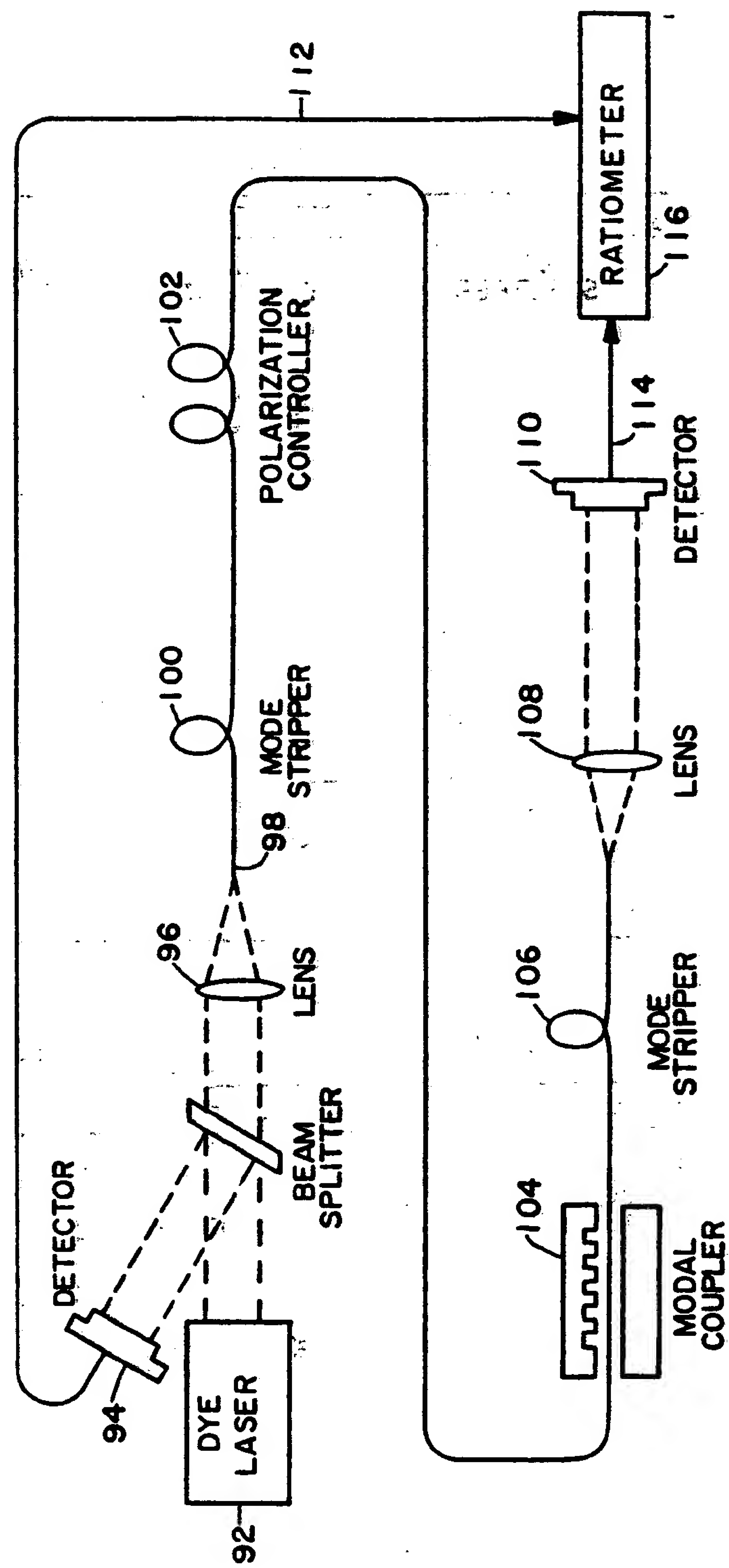

DYE LASER
92
DETECTOR
94
BEAM SPLITTER
LENS
96
98
MODE STRIPPER
100
POLARIZATION CONTROLLER
102
112
RATIOMETER
116
114
DETECTOR
110
LENS
108
MODE STRIPPER
106
104
MODAL COUPLER

FIG. 12

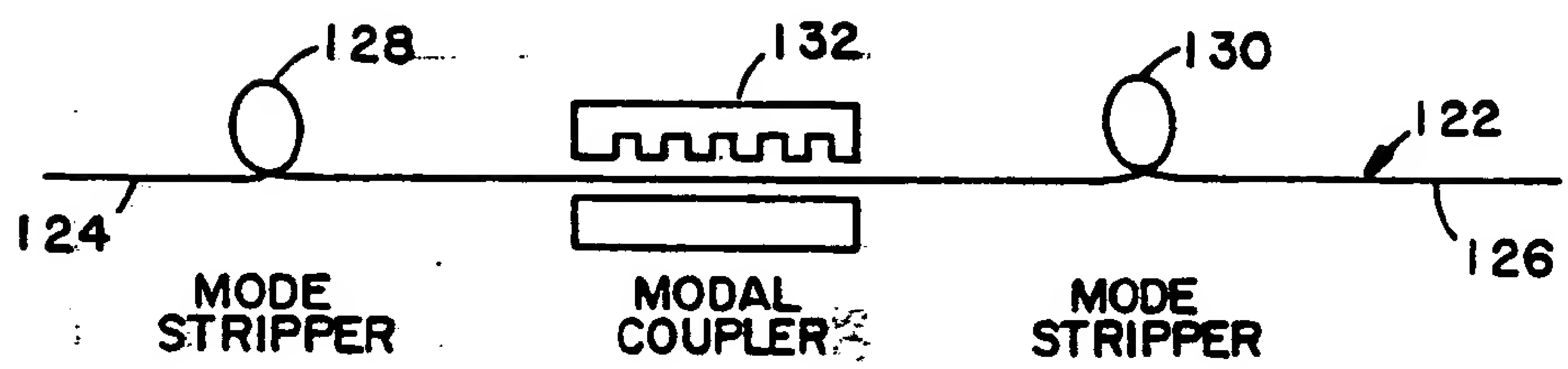

128
132
130
122
124
126
MODE
STRIPPER
MODAL
COUPLER
MODE
STRIPPER

FIG. 13

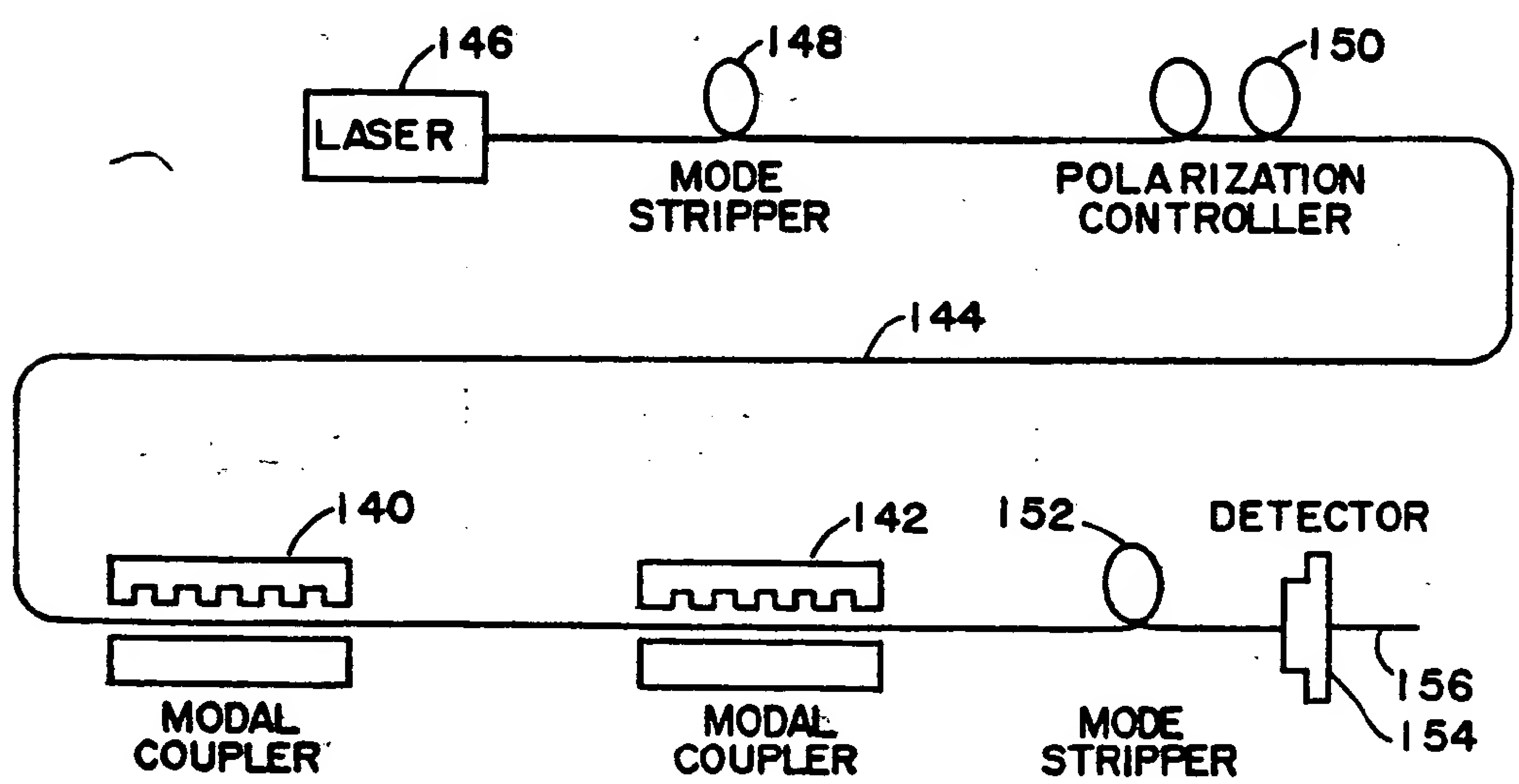

146
148
150
LASER
MODE
STRIPPER
POLARIZATION
CONTROLLER
144
140
142
152
DETECTOR
156
154
MODAL
COUPLER
MODAL
COUPLER
MODE
STRIPPER

FIG. 14